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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

This Issue

VISCOSITY-1

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VISCOSITY-I

DURING the past decade or so, there has been an ever increasing need for lubricants and hydraulic fluids for use in mechanisms operating under extremely difficult conditions. The high speeds encountered today in some bearings and gears were unheard of, or were barely envisioned only a few years ago. Not only speeds but loads and accompanying pressures are also increasing. Operating temperatures are becoming more extreme. In some aircraft operations, hydraulic oils must perform satisfactorily down to 65°F. below zero. At the other extreme, there is need for lubricants capable of operating at 1200°F.

Lubricants today are also subjected to increasing mechanical shearing forces and sustained turbulent effects which put additional strains on them.

Temperature, pressure and shearing problems have greatly widened the horizons of lubrication and have stimulated considerable research regarding its basic principles. The result has been an increasing interest in, and knowledge of, viscosity since lubrication and viscosity are intimately connected. In fact, viscosity is the most important single property of a liquid or gaseous lubricant.

For convenience in printing and distribution, this comprehensive article on viscosity has been divided into two parts. The first part, contained in this issue, reviews fundamental principles, and describes common methods of measuring viscosity. The second part to be presented in the February 1961 issue of this publication will discuss: viscosity unit conversions; the effects of temperature, shear, pressure, and nuclear radiation on viscosity; viscoelasticity; film lubrication; liquid flow in pipes and hydraulic systems.

FUNDAMENTAL PRINCIPLES

Viscosity is the internal resistance exhibited as one portion or layer of a liquid is moved in relation to another portion. It is due to the internal friction of the liquid molecules moving past each other. Since temperature is a measure of molecular motion, temperature is the most important variable affecting the viscosity of a liquid and must always be stated in conjunction with the viscosity.

Lord Kelvin expressed the thought that to describe clearly a concept, one should assign numbers or mathematical expressions to it. More than 200 years ago, Sir Isaac Newton treated viscosity in just such a manner by defining it and deriving its descriptive equation as illustrated in Figure 1. Suppose that a film of liquid, such as mineral oil, is placed between two parallel planes with the bottom one stationary, and that the upper plane of area A is moved with a constant velocity of V by means of a force F. Oil molecules are visualized as small balls which roll along in layers between the flat planes. Since the oil will "wet" and cling to the two surfaces, the bottommost layer will not move at all, the uppermost will move with a velocity V and each intermediate layer will move with a velocity directly proportional to its distance from the sta-

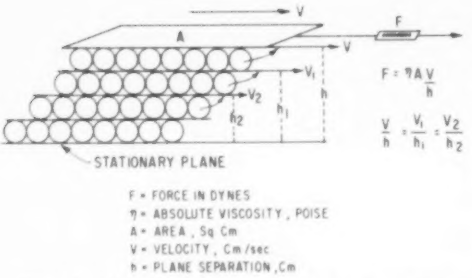


Figure 1 — Newton's theory of streamline or viscous flow.

tionary bottom plane. This orderly type of movement in parallel layers is known as *streamline, laminar* or *viscous flow*. The *force* per unit area, $\left(\frac{F}{A}\right)$ required to impart motion to the layers is called the *shear stress* while the movement of one layer of oil relative to another is the *shear strain rate*. The *rate of shear* (R) of a particular layer, sometimes called the *velocity gradient*, is defined as the ratio of its velocity to its perpendicular distance from the stationary surface, and is constant for each layer: $R = \frac{V}{h} = \frac{V_1}{h_1} = \frac{V_2}{h_2}$ etc. Newton correctly deduced that the force (F) required to maintain a constant velocity (V) of the upper plane was proportional to the area (A) and to the velocity gradient or rate of shear $\left(\frac{V}{h}\right)$. Thus in equation form $F = \eta A \frac{V}{h}$ where η (eta) is the proportionality constant or the *coefficient of viscosity* or simply *viscosity* of the absolute or dynamic type. By rearranging the equation, absolute viscosity is thus defined as

$$\eta = \frac{\text{Shear stress}}{\text{Rate of shear}} = \frac{\frac{F}{A}}{\frac{V}{h}}$$

If the metric system of units (centimeter, gram, second) is used as shown in Figure 1, shear stress $\left(\frac{F}{A}\right)$ is expressed in *dynes per square centimeter*, rate of shear $\left(\frac{V}{h}\right)$ in *reciprocal seconds*, and absolute viscosity in *poises* (in honor of Dr. J. Poiseuille who studied the flow of liquids in capillaries). Since the poise is a rather large unit, the *centipoise* (one hundredth of a poise) is customarily used. Pure water at a temperature of 68.4°F. has an absolute viscosity of one centipoise.

If the English system of units (foot, pound, second) is used, the unit of absolute viscosity is the *pound-second per square inch* or *reyn* (in honor of the English scientist Osborne Reynolds). Since the reyn is an extremely large unit, the newton (one millionth of a reyn) is more convenient. Conversion between metric and English system units of absolute viscosity can be made on the basis that one reyn or one million newtons is equal to 68,950 poises or 6,895,000 centipoises.

Newtonian Liquids

Newton further deduced that the viscosity of a given liquid should be constant at any particular temperature and pressure and independent of the rate of shear as illustrated in Figure 2. In such "Newtonian fluids", shear stress is directly proportional to rate of shear. At temperatures above their cloud points most mineral oils are Newtonian fluids.

Non-Newtonian Materials

The viscosities of some materials, such as greases and polymer-thickened mineral oils, are affected by shearing effects and these materials are termed "non-Newtonian". In other words the viscosity of a non-Newtonian fluid will depend on the rate of shear at which it is measured. Since a non-Newtonian fluid can have an unlimited number of viscosity values (as the shear rate is varied) the term *apparent viscosity* is used to describe its viscous properties. Apparent viscosity is expressed in absolute units and is a measure of the resistance to flow at a given rate of shear. It has meaning only if the rate of shear used in the measurement is also given and is obtained experimentally by measuring and dividing the shear stress by the rate of shear. A "rheogram" or "flow curve" relating shear stress to rate of shear is frequently used to completely describe the viscous properties of a non-Newtonian material.

Non-Newtonian materials may be divided into five types: plastic, pseudo-plastic, dilatant, thixotropic and rheopectic. Figure 3 presents characteristic rheograms in which shear stress (e.g. pressure

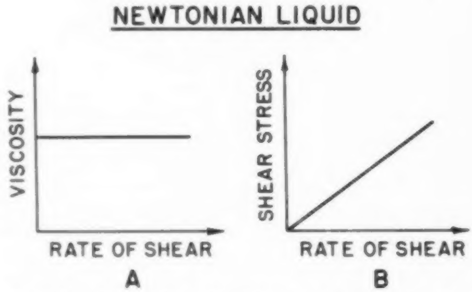


Figure 2 — A. Viscosity independent of shear rate for Newtonian liquid.
B. Flow curve for same liquid.

in a steady-flow system) is plotted against rate of shear (e.g. flow velocity). Figure 4 illustrates how the apparent viscosities of non-Newtonian materials vary with changing rates of shear.

As illustrated in curve 1 of Figure 3 a *plastic* material, such as a grease, putty or molding clay, is characterized by a "yield point" or "yield value". This means that a definite minimum stress or force must be applied to the material before any flow takes place. As shown in Figure 4 its apparent viscosity approaches infinity as the rate of shear approaches zero. From a rheological standpoint[1] tomato catsup is a common example of a plastic material. If a bottle is shaken only gently, its contents may not flow out because the "yield point" has not been exceeded. However, if the bottle is struck or shaken more vigorously, the yield point is exceeded, the viscosity is reduced, and the catsup gushes forth.

While a *pseudo-plastic* fluid has no yield point, its apparent viscosity also decreases with increasing shear rates but stabilizes only at very high rates of shear. Many emulsions such as water base fluids and resinous materials show this type of behavior.

[1] Rheology: The science treating of deformation and flow of matter.

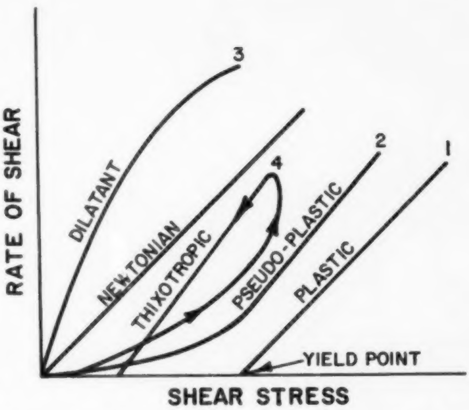


Figure 3 — Flow curves or shear characteristics of various types of materials.

Oppositely, the apparent viscosity of *dilatant* fluid increases as the rate of shear increases. Such a fluid often solidifies at high rates of shear. Examples are pigment-vehicle suspensions such as paints and printing inks, and some starches.

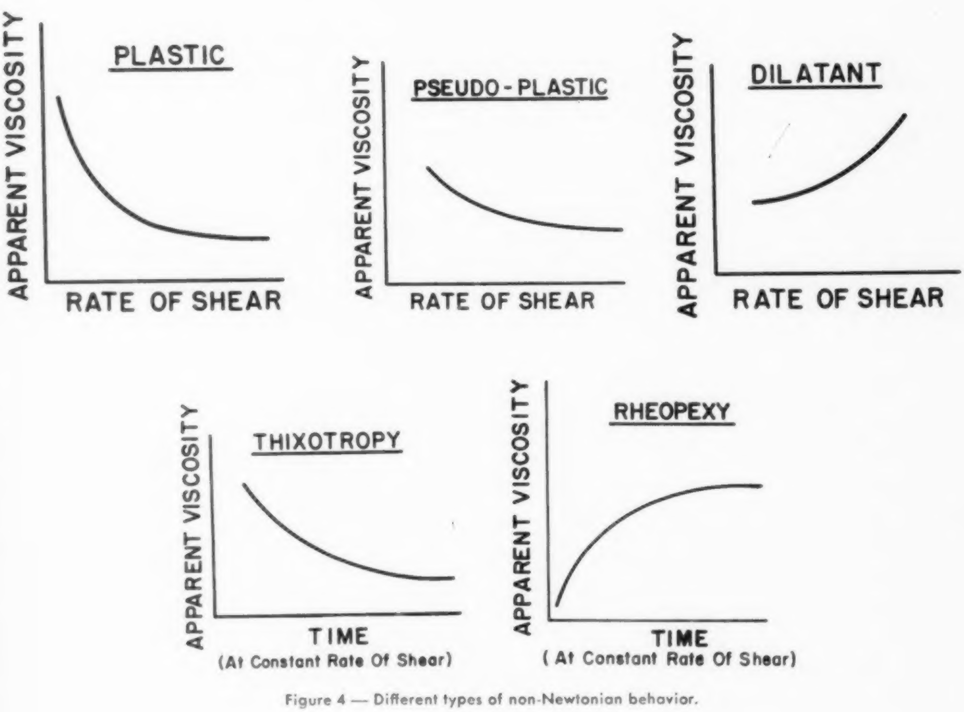


Figure 4 — Different types of non-Newtonian behavior.

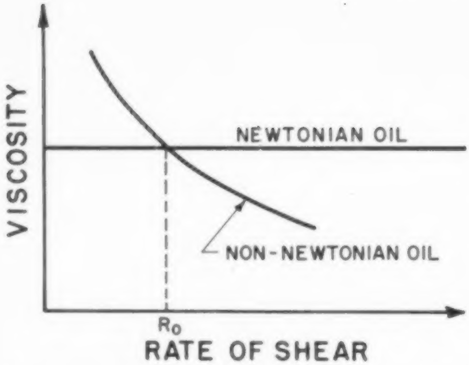


Figure 5 — Viscosity vs. rate of shear for a Newtonian oil and a non-Newtonian oil.

The three fluids described above,——plastic, pseudo-plastic and dilatant,——are also known as time-independent non-Newtonian fluids, since their rheological or flow properties are independent of time. The rate of shear at any point in the fluid is a simple function of the shear stress at that point.

On the other hand, the flow properties of the other two non-Newtonian materials,——thixotropic and rheopectic,——are dependent on time. The apparent viscosity of these more complex fluids depends not only on the magnitude of the shear rate but also on the length of time during which shear has been applied.

If a *thixotropic* fluid is subjected to a constant rate of shear for some time, its structure is gradually broken down and its apparent viscosity decreases to some minimum value. When the shear effect is removed and the fluid is at rest, the structure rebuilds gradually and apparent viscosity increases with time to the original value as indicated by the hysteresis loop in Figure 3 and by Figure 4. This is called *reversible thixotropy*. If, however, upon removing the shear stress, a value less than the original viscosity is obtained with time, the phenomenon is known as *irreversible thixotropy*. Some oils containing high molecular weight polymers, and mineral oils at temperatures below their cloud point show this latter effect.

During rotary drilling of deep oil wells, a very special "drilling mud" with thixotropic properties is pumped down the hollow drill stem to force cuttings back to the surface. As long as the mud is agitated by rotation of the drill stem and by pumping, it remains fluid and removes drilling debris. However, whenever drilling is stopped, the drilling mud solidifies to a gel, holds the cuttings in suspension, and thereby prevents them from settling and interfering with subsequent drilling.

Quicksand is also thixotropic since it becomes more and more fluid when agitated; therefore anyone caught in this water-and-sand mixture improves his chance of survival by remaining as motionless as possible.

If a *rheopectic* fluid is subjected to a constant rate of shear for a given period of time, its apparent viscosity increases to some maximum value. Upon cessation of shearing and resting for a time, its apparent viscosity decreases again.

Some greases are intentionally manufactured to have partial rheopectic properties, which facilitate pumping from a drum or central grease storage in which the grease is in a relatively fluid condition. Upon shearing in a bearing, however, the grease builds up to a higher apparent viscosity or consistency and stays in place. Such a grease does not have full rheopectic characteristics however, since after shearing and resting, it still retains a higher consistency.

Since the viscosity of a non-Newtonian lubricant is dependent upon the rate of shear acting on it, the importance of measuring viscosity at various shear rates that will be encountered in the use of such a lubricant can be readily seen. In some machine elements, shear rates up to 3 million reciprocal seconds may be encountered while in other applications only a few reciprocal seconds or a few tenths are the order of magnitude. In dispensing greases, shear rates as low as 0.1 reciprocal seconds are sometimes encountered, while leakage from housings during periods of shutdown involves an even lower range. Instruments for these measurements are described in a later section.

As illustrated by Figure 5, the determination of viscosity of a non-Newtonian liquid at only one shear rate is not usually sufficient. Incorrect conclusions would be drawn and application difficulties would be invited if the viscosities of a Newtonian

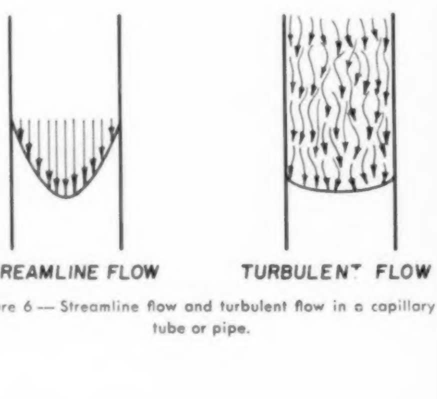
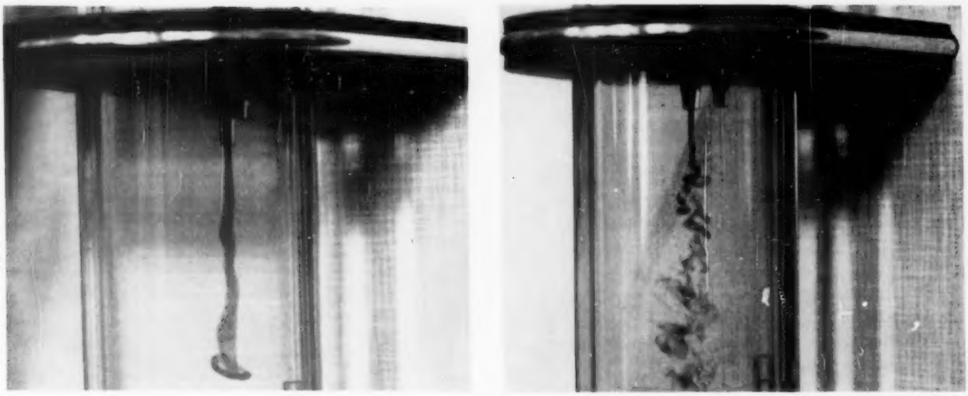


Figure 6 — Streamline flow and turbulent flow in a capillary tube or pipe.



Courtesy of Q.V.F., Limited

Figure 7 — Apparatus for demonstrating streamline (laminar) and turbulent flow.

and a non-Newtonian oil were measured at some specific shear rate, R_0, where the two curves happened to cross each other. While both oils have the same apparent viscosity at this one point, the remainder of their viscosity—shear curves are entirely different.

Viscosity Measurement with Capillaries

Poiseuille determined that the flow of water (a simple Newtonian liquid) through a capillary tube was governed by the following equation, now known as *Poiseuille's Law*:

$$v = \frac{\pi P r^4}{8 L \eta}$$

in which v is the volume in cubic centimeters flowing in one second, P is the pressure difference between the tube ends in dynes per square centimeter, r is the radius of the tube in centimeters, L is its length in centimeters and η (eta) is the absolute viscosity in poises.

By measuring the time in seconds (T) required for a certain volume (V) of any liquid to flow through a capillary, the absolute viscosity in poises can be calculated from the following similar equation:

$$\eta = \frac{\pi P r^4 T}{8 V L}$$

This relationship holds only if the flow velocity in the capillary is below a certain critical value where the flow is laminar or streamline in nature as shown in the left portion of Figure 6.

Turbulent Flow and Reynolds Number

Poiseuille found that his equations were no longer valid if the pressure, and therefore the velocity of flow were increased above some critical value. About 1883 Osborne Reynolds determined that this invalidity was caused by a relatively sudden change from laminar to turbulent flow, in which the liquid moved mainly in erratic eddy currents as illustrated in the right hand portion of Figure 6. Reynolds determined further that the ***critical velocity*** (V_c) at which this occurred was related to the dimensionless function $\frac{DV\rho}{\eta}$, now called the *Reynolds number* where D is the inside diameter of the tube, V is the velocity of the liquid, ρ (rho) is the density of the fluid and η (eta) is its absolute viscosity. Since this function is dimensionless, it is meaningful only when consistent units, i.e. units within a given measurement system, are used and quoted. At a Reynolds number of about 2000 and higher, flow becomes turbulent, therefore critical velocity (V_c) can be calculated from the equation:

$$V_c = \frac{2000\eta}{D\rho}$$

The states of laminar and turbulent flow as demonstrated in a commercially available apparatus are shown in Figure 7.

Since $\frac{\eta}{\rho}$ (the ratio of absolute viscosity to density) is also used in several other equations dealing with viscosity and is also very useful in the study of hydraulics, the term "***kinematic viscosity***", with symbol ν (nu) have been assigned to it. The basic unit of kinematic viscosity is the ***stoke,*** named in honor of Sir George Stokes for his contributions to the science of fluid mechanics. The centistoke (one hundredth of a stoke) is more generally used however.

In viscometry measurements by means of capillary tubes, it is therefore necessary to avoid turbu-

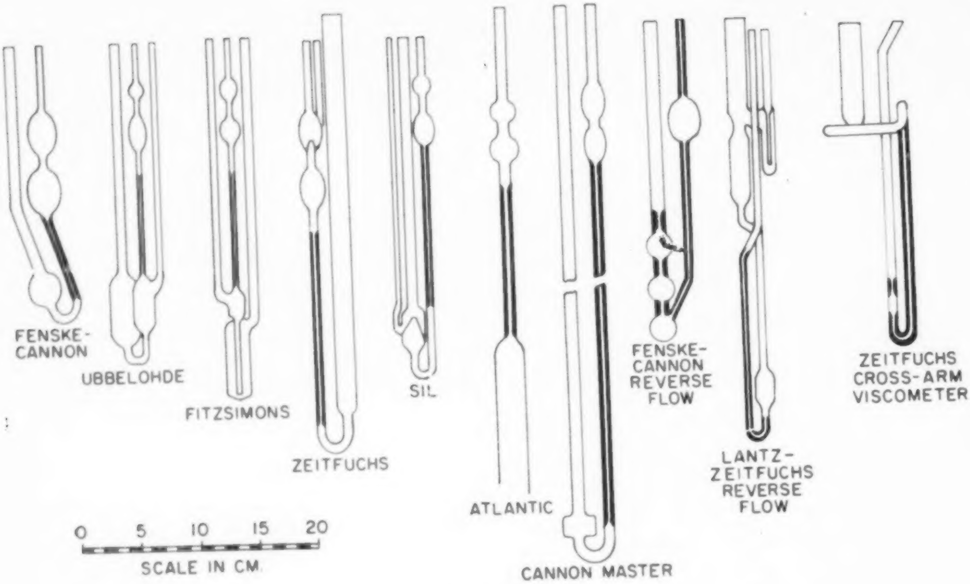


Figure 8 — Ten types of capillary viscometers.

lence. A small error does occur, however because of varying convergence and divergence of liquid flow at the capillary ends. Couette studied this "end effect" and devised the "Couette correction".

A second correction to Poiseuille's equation, called the "kinetic energy correction", is necessary because only part of the force applied to a liquid in a tube is used in overcoming viscous forces, while the remainder is "wasted" by imparting kinetic energy to the outflow. The kinetic energy correction is important for viscosities below 1.5 centistokes.

Viscosity measurement in a capillary is not as formidable as the foregoing might indicate. Poiseuille's equation has been modified to include the necessary corrections and the dimensions of any particular capillary. When flow impulse is furnished by gravity and the time in seconds (T) for the flow of a given volume of liquid is measured the equation becomes:

$$(3) \qquad \frac{\eta}{\rho} = \nu = AT - \frac{B}{T}$$

Because gravity flow is used, this equation gives kinematic viscosity, ν, directly. A and B which are constants for all practical purposes are determined for any particular capillary by measuring the time of flow for two liquids of known but different kinematic viscosities. If ν_1 and ν_2 are the kinematic viscosities of two known liquids and T_1 and T_2 their respective flow times, then:

$$A = \frac{\nu_2 T_2 - \nu_1 T_1}{T_2{}^2 - T_1{}^2}$$

$$\text{and } B = \frac{T_1 T_2}{T_2{}^2 - T_1{}^2}\left(\nu_2 T_1 - \nu_1 T_2\right)$$

The term $\frac{B}{T}$ may be disregarded if flow time is relatively long, or if it amounts to only 0.1 per cent or less of the AT term, without seriously affecting the accuracy of results since this would be only a small fraction of the main term, AT. However, if efflux time is short, or very accurate results are required, then $\frac{B}{T}$ must be used.

From a theoretical point of view, confirmed by experimentation, the capillary viscometer constant, B, is actually not a constant but increases as the Reynolds number increases.

Ishii and others[2], and Cannon and co-workers[3] recently investigated this kinetic energy correction problem and each derived a separate equation for the accurate calibration of capillary instruments. Ishii uses the empirical formula:

$$\nu = AT\left(1 - 10^{-\alpha T^{\beta}}\right)$$

where A, α, and β are constants obtained from known reference liquids with a mathematical and graphical treatment. Cannon developed the equation, $\nu = AT - \frac{E}{T^2}$ where A and E are the instru-

[2] Ishii, N., Wakana, A., Kinoshita, M.—1959 Fifth World Petroleum Congress, Papper 27, Section V.

[3] Cannon, M. R., Manning, R. E., Bell, J. D.,—Analytical Chemistry, 32, 355, March 1960.

ment constants determined from viscosity standards and pure known hydrocarbons.

VISCOMETERS

If the number of viscometers (or "viscosimeters") that have been developed for the determination of viscosity is any indication of the importance of that property, then viscosity, indeed, is the most significant single characteristic of a lubricating oil.

The following eight different techniques are used to determine viscosity by measuring:

1. *Time of flow* of a definite quantity of the liquid propelled by gravity through a short tube or a capillary.
2. *Torque* required to rotate a cylinder, disc or paddle in the liquid at a fixed speed.
3. *Torque* exerted on a disc suspended in a rotating cup containing the liquid.
4. *Rotational speed* of a cylinder or disc driven in the liquid by a known constant torque.
5. *Time of fall* through the liquid of a ball or cylindrical object.
6. *Time of rise* of an air bubble through the liquid held in a tube.
7. *Rate of damping* of ultrasonic waves induced in the liquid.
8. *Pressure drop* through a capillary.

The second, third and fourth methods are variations of the Couette or rotational viscometer.

Because of its large effects on viscosity, the temperature of the fluid in all viscometers, but especially the capillary type, must be accurately controlled. One authority specifies an accuracy of $\pm 0.02^\circ$F.

Capillary Viscometers

In the petroleum industry many viscosity determinations are made with capillary type viscometers. The American Society for Testing Materials (ASTM) Method D-445 prescribes the standard procedure for measuring kinematic viscosity and describes nine of the capillary viscometers illustrated in Figure 8. The first six are used for transparent liquids, the Cannon Master for calibration work, and the last three are designed chiefly for opaque liquids. Such a large number of capillary type instruments is the result of continuing effort to minimize certain errors such as surface tension and kinetic energy, to cover wider ranges of viscosities and temperatures and to afford operational ease and conveniences. For example Cannon recently patented an improved Ubbelohde viscometer having such dimensions that the kinetic energy correction $\frac{B}{T}$, can be disregarded for viscosities as low as 0.4 centistokes.

In calibration work, freshly distilled water is used as the primary standard. Its kinematic viscosity at 20°C. is 1.002 centipoise[4] or 1.0038 centistokes. This is used to calibrate a master viscometer such as one shown in Figure 8 in terms of a constant A in the equation $\nu = AT - \frac{B}{T}$. For this instrument, the correction term, $\frac{B}{T}$, is not needed. With a calibrated master viscometer, the viscosity values of several oils are determined and these are then used as secondary standards to calibrate instruments used for routine testing.

A non-Newtonian fluid can be identified by measuring its viscosity in several capillary viscometers with different capillary diameters (and therefore different shear rates) and noting any significant variations among the several viscosities.

Short Tube or Orifice Viscometers

Five other efflux-time instruments for viscosity measurements are sometimes used in the petroleum industry. These are the Saybolt Universal and Saybolt Furol used mainly in the United States, the Redwood No. 1 (Standard) and Redwood No. 2 (Admiralty) used in Great Britain, and the Engler used chiefly in Germany and other countries on the continent. All five are *empirical* instruments in that the time of outflow of an arbitrary constant amount of an oil is quoted as a measurement of the viscosity of the oil. The instruments are similar in basic principle but differ in various dimensions and in the amount of oil used. As a consequence all assign different viscosity numbers to the same oil, therefore any empirical viscosity is meaningful only when the viscometer and temperature are also named.

1. Saybolt Universal Viscometer. Illustrated in Figure 9, this instrument measures the efflux time in seconds for 60 ml. of oil at some specified Fahrenheit temperature such as 70, 100, 130 or 210 degrees. Viscosities are quoted in terms of Saybolt Universal seconds (SUS). The instrument should not be used on oils with an efflux time of less than 32 seconds. Its orifice is 0.4823 inches (12.25 mm) long and 0.0695 inches (1.77 mm) in diameter.

2. Saybolt Furol Viscometer. Similar in appearance to the Saybolt Universal, but using an orifice 0.4823" long and 0.1240" in diameter, this instrument also measures the efflux time in seconds for 60 ml. of oil. A Furol viscosity is about one-tenth the Universal viscosity on the same oil, however the Furol is used chiefly for petroleum products having viscosities greater than 1000 SUS, such as heavy fuel oils. In fact the word "Furol" is a contraction of the words "fuel" and "road oil".

[4] Swindells, J. F., Coe, J. R., Godfrey, T. B., J. Res. Nat. Bur. Stand. Vol. 48, 1, 1952.

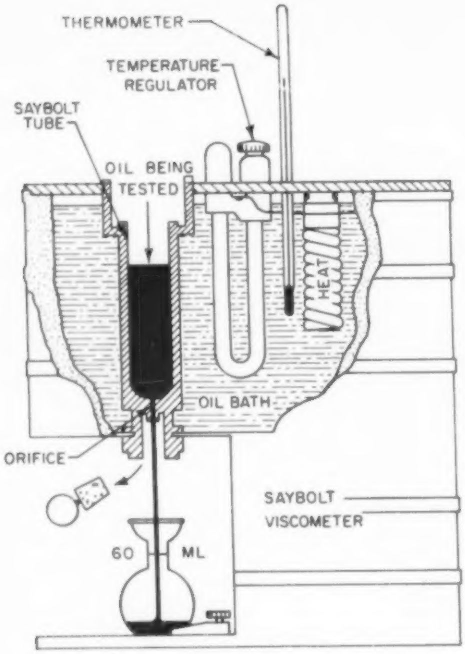
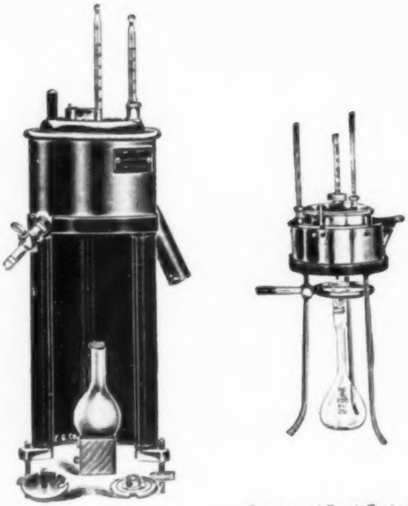


Figure 9 — Saybolt viscometer.



Courtesy of Emil Greiner Co.

Figure 10 — Redwood No. 1 and Engler Viscometers.

3. Redwood No. 1 (Standard) Viscometer. Pictured in Figure 10, this instrument uses an orifice 10 mm long and 1.62 mm in diameter, measures the efflux time at the test temperature for 50 ml. of oil, and quotes it as "Redwood seconds".

4. Redwood No. 2 (Admiralty) Viscometer. Similar in appearance to the Redwood No. 1, this instrument employs an orifice 50 mm long and 3.80 mm in diameter, which gives an efflux time on a given oil that is approximately one-tenth of the Redwood No. 1 viscometer. As indicated by its name it is used mainly in testing those fuel oils for the British Navy which would have viscosities greater than 2000 seconds in the Redwood No. 1.

5. Engler Viscometer. This instrument, also pictured in Figure 10, measures the efflux time in seconds for 200 ml. of oil which may be quoted as "Engler seconds". To minimize differences among instruments however, Engler viscosities are usually expressed as "Engler degrees" (E°), which is the ratio of the efflux time of 200 ml. of oil at the test temperature to the efflux time of 200 ml. of water at 20°C. The Engler orifice tapers from 2.9 to 2.8 mm in its 20 mm length with an average diameter of 2.85 mm.

Although the capillary viscometers are more accurate and require less sample and time than the "short-tube" instruments, a capillary is more easily plugged by emulsions or "dirty" oils, consequently a short tube instrument may be preferred in such instances.

In the United States viscosities are increasingly determined with capillary viscometers, and the results then converted to such empirical units as Saybolt Universal seconds which are widely used in such "public specifications" as the SAE (Society of Automotive Engineers) Crankcase Oil Viscosity Classification.

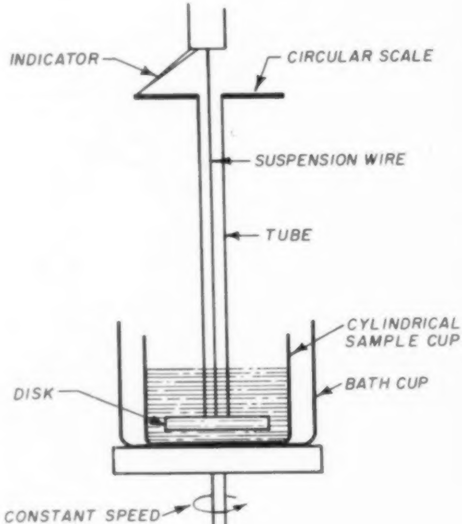


Figure 11 — MacMichael viscometer.

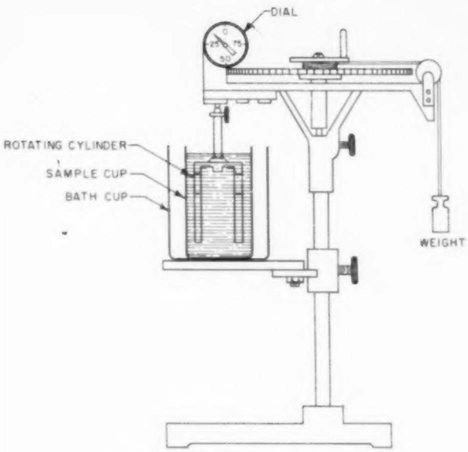


Figure 12 — Stormer viscometer.

Rotational Viscometers

Based on Newton's fundamental law of viscosity as illustrated in Figure 1 but employing two concentric cylindrical or conical surfaces instead of planes, a rotational viscometer measures viscosity by determining the direct or reactive force required to hold one cylinder stationary when the other is rotated at a constant speed.

As examples, the MacMichael viscometer shown in Figure 11 measures viscosity by determining the torque exerted on a disc or cylinder suspended by a wire in a cup rotating at constant speed. The Stormer viscometer illustrated in Figure 12 consists of a rotating cylinder immersed in a fixed cup containing the sample. The cylinder is rotated by a weight and the time for 100 revolutions (as registered on the dial) is a measure of the viscosity. The MacMichael and Stormer viscometers are used mainly on very viscous liquids.

The Brookfield Synchro-Lectric Viscometer illustrated in Figures 13 and 14 dispenses with one of the cylinders by measuring the force required to rotate a cylinder or spindle in the fluid at constant speed. By using different speeds of rotation, different shear rates are obtained, hence the instrument can measure both the viscosity of Newtonian and the apparent viscosity of non-Newtonian materials.

High Rate of Shear Rotational Viscometer

As mentioned previously, the apparent viscosity of non-Newtonian lubricants depends on the rate of shear. In order to study the shear behavior of non-Newtonian materials at high shear rates, a ro-

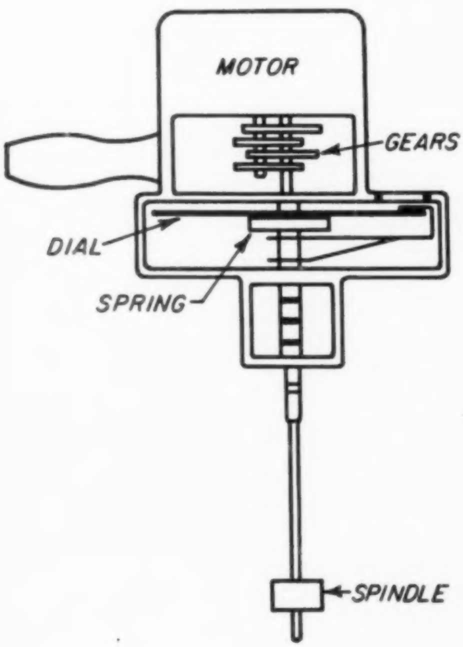
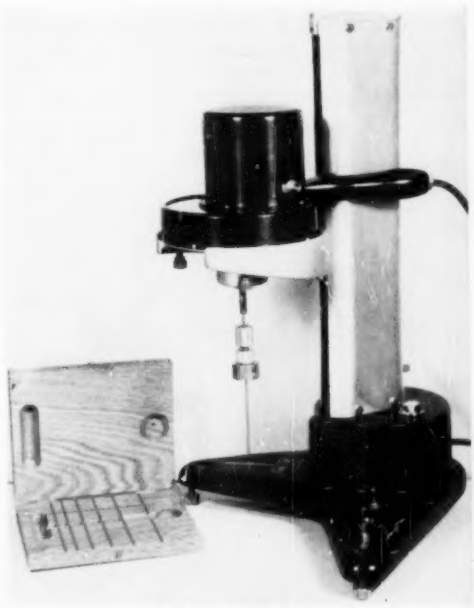


Figure 13 — Schematic of Brookfield Synchro-Electric viscometer.



Courtesy of Brookfield Engineering Laboratories, Inc.

Figure 14 — Brookfield Synchro-Lectric viscometer mounted on helipath stand.

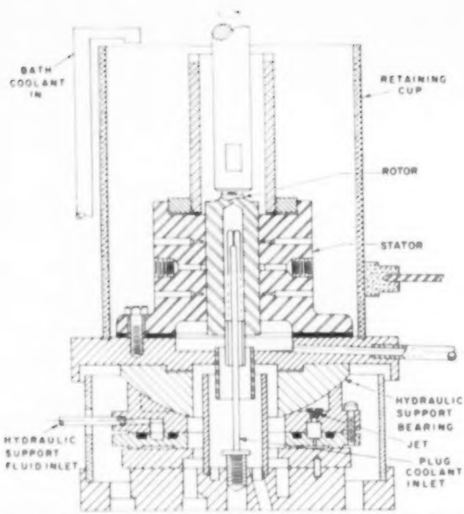


Figure 15 — Section through high rate of shear rotational viscometer.

tational viscometer has been developed[5] which is capable of shear rates up to 1,000,000 $sec.^{-1}$, (reciprocal seconds). Figure 15 shows a section through the instrument and Figure 16 a pair of test cylinders. The inner cylinder is rotated at a constant speed in the range 12 to 1000 rpm and the force required to keep the outer cylinder from rotating is measured. This force is a direct measure of the viscosity. Four inner cylinders are available giving oil film thicknesses of 0.00050 to 0.00005 inches and producing maximum shear rates of

[5] Barber, E. M., Muenger, J. R., Villforth, F. J.—Analytical Chemistry 27, 425, March 1955.

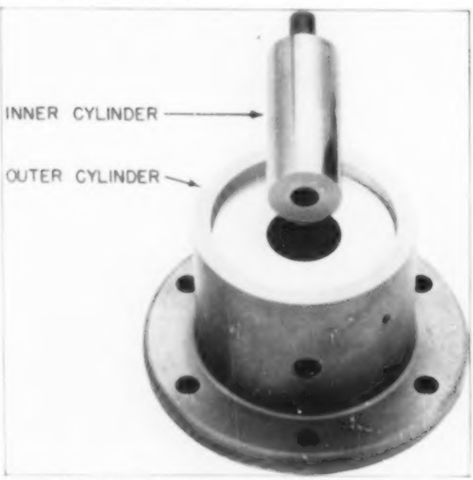
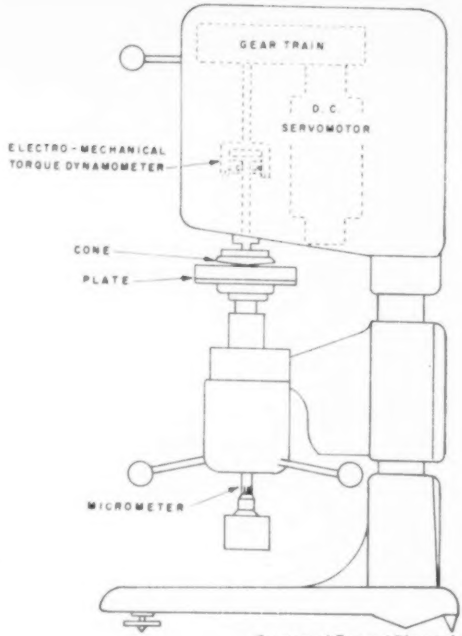


Figure 16 — Pair of test cylinders for high shear rate rotational viscometer.



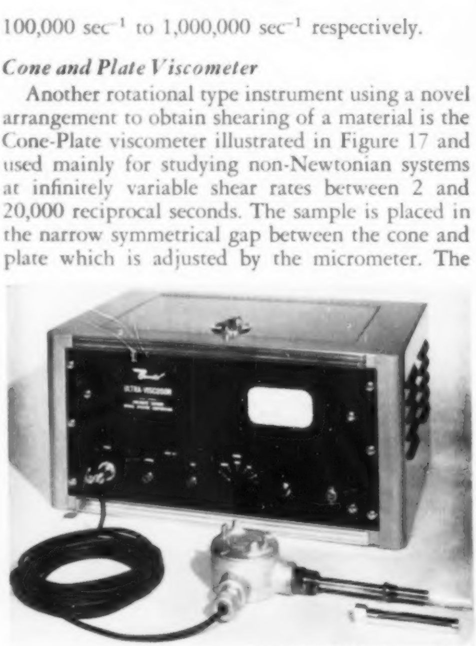
Courtesy of Ferranti Electric Inc.

Figure 17 — Section through Ferranti-Shirley Cone-Plate viscometer.

100,000 sec^{-1} to 1,000,000 sec^{-1} respectively.

Cone and Plate Viscometer

Another rotational type instrument using a novel arrangement to obtain shearing of a material is the Cone-Plate viscometer illustrated in Figure 17 and used mainly for studying non-Newtonian systems at infinitely variable shear rates between 2 and 20,000 reciprocal seconds. The sample is placed in the narrow symmetrical gap between the cone and plate which is adjusted by the micrometer. The



Courtesy of Bendix Aviation Corp.

Figure 18 — The Bendix Ultra-Viscoson.

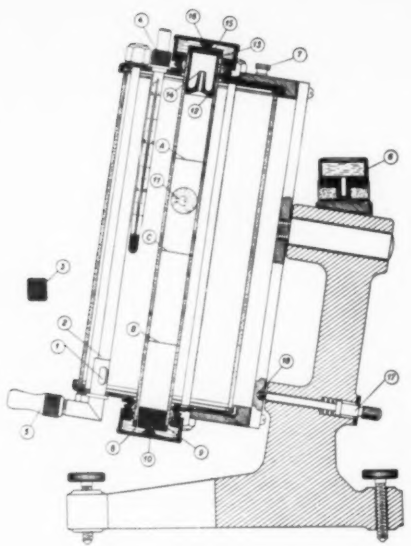


Figure 19 — Section through a Hoeppler viscometer.

plate is stationary while the cone rotates at constant or programmed variable speeds. The viscous force of the sample on the cone exerts a torque on the electro-mechanical dynamometer which is a measure of the viscosity.

Ultrasonic Viscometer

An instrument used for the automatic measurement and continuous recording of viscosity, for example the oil in a refinery process stream, is the Bendix Ultra-Viscoson illustrated in Figure 18. This consists of a probe inserted in the stream to be measured and an electronic computer. Ultra high-frequency vibrations are applied to the probe. These ultrasonic vibrations are damped depending on the viscosity and density of the material. The resulting vibration rate is measured by the electronic computer and converted to the product of absolute viscosity times density. To obtain viscosity this product is divided by the density. Both Newtonian and non-Newtonian liquids can be measured.

Falling Sphere Viscometer

The absolute viscosity (η) of a fluid can be determined by measuring the dropping velocity of

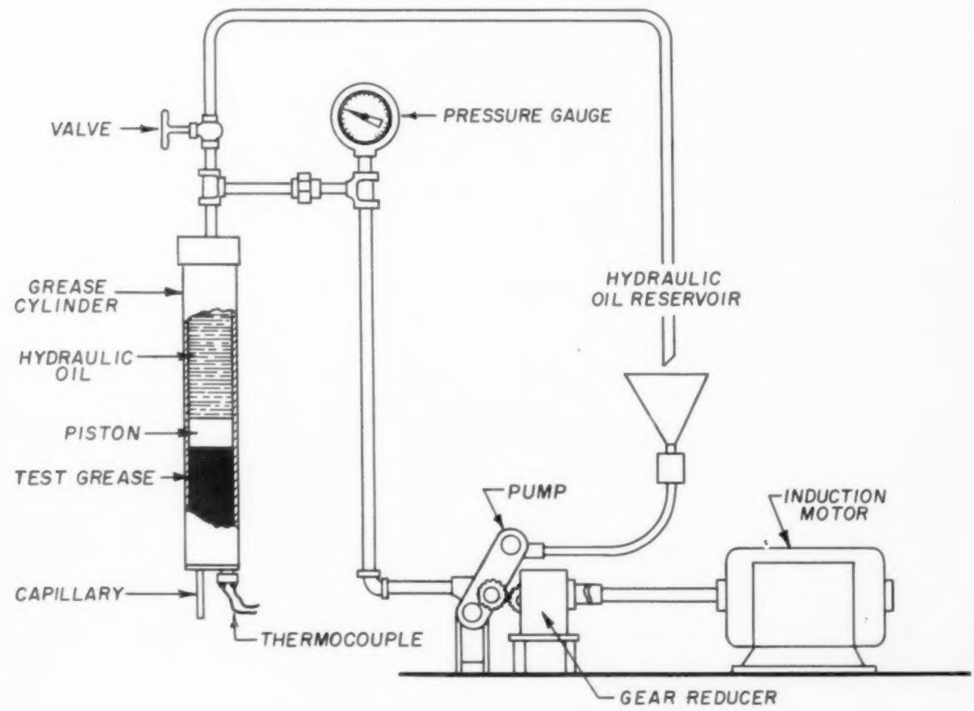


Figure 20 — Schematic diagram of a pressure viscometer.

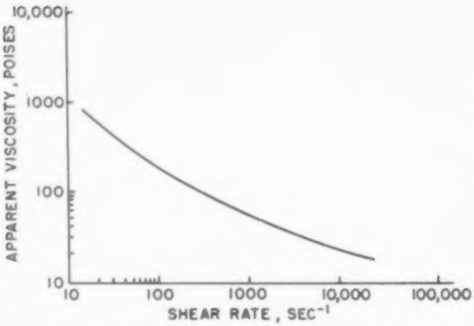


Figure 21 — Typical relationship between apparent viscosity and shear rate as measured in a pressure viscometer on a No. 2 NLGI grade grease at 77°F.

a ball through the fluid in a tube (preferably of glass so that the ball can be easily observed). This is based on Stokes' Law of falling bodies in a viscous medium:

$$\eta = \frac{2}{9} \frac{(S_b - S_f) g r^2}{V}$$

where S_b = specific gravity of the ball
S_f = specific gravity of the fluid at the test temperature
g = acceleration due to gravity (980 cm/sec^2)
r = radius of ball, centimeters
V = velocity of falling ball, centimeters per second

Figure 19 shows the Hoeppler viscometer in which measurement is made by timing the fall (T, in seconds) of a ball through a calibrated distance between two marks on the glass tube. The glass tube, having a volume of about 30 ml., is mounted in a glass water jacket at an angle of 10° from the vertical, the optimum inclination to assure reproducible results. Absolute viscosity is equal to T $(S_b - S_f)$ B, where B is a constant that is characteristic of the particular ball. Balls made of different materials and sizes permit viscosity measurements through the very wide range between 0.01 and 1 million centipoises, i.e. from gases through very viscous liquids.

Pressure Viscometer

Since the viscosity and flow properties of a non-Newtonian material like grease depend on the rate of shear to which it is subjected, a pressure viscometer like that described in ASTM Method D1092-58T ("Apparent Viscosity of Lubricating Greases") and diagrammed in Figure 20 is widely used to produce controlled shear rates and to measure the corresponding apparent viscosities.

In such an instrument the grease sample is usually forced through a capillary at constant shear rate by pressure from a floating piston actuated by the fixed displacement gear pump of the hydraulic system. By using combinations of eight different capillaries and two pump speeds, the effects of sixteen different shear rates may be investigated. A thermostatically-controlled air or liquid bath around the pressure cylinder is used to control chosen temperatures between minus 100 and plus 100 degrees F. within ± 0.5°F. Apparent viscosity is calculated from Poiseuille's equation by substituting the appropriate values of pump pressure, capillary diameter and pump flow rate. Plotted on log-log paper Figure 21 presents the results on a NLGI Grade 2 grease.

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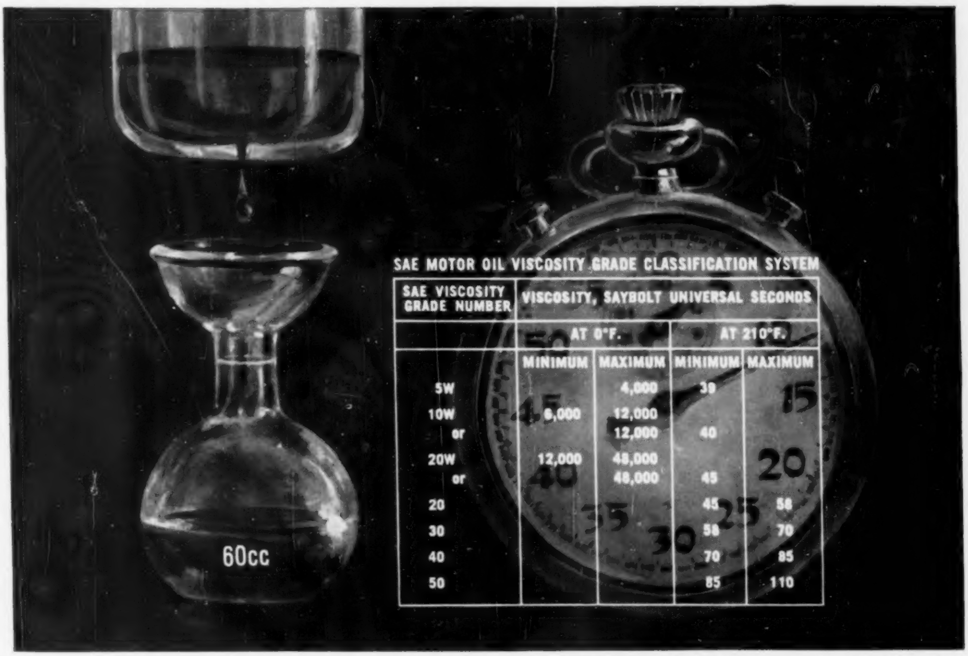

SAE MOTOR OIL VISCOSITY GRADE CLASSIFICATION SYSTEM

SAE VISCOSITY GRADE NUMBER	VISCOSITY, SAYBOLT UNIVERSAL SECONDS			
	AT 0°F.		AT 210°F.	
	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
5W		4,000	39	
10W	6,000	12,000		
or		12,000	40	
20W	12,000	48,000		
or		48,000	45	
20			45	58
30			58	70
40			70	85
50			85	110

Viscosity is measured by the time required for 60cc of oil in the Saybolt Viscosimeter Tube to flow through a standard opening, at a given temperature.

What viscosity really means

Viscosity is a liquid's *resistance to flow.* It varies among different liquids, and increases to some extent as temperature drops.

In the United States, the viscosity of oils is usually determined with a Saybolt Universal Viscosimeter. It simply measures the time in seconds required for a given quantity of oil to drain through a standard hole at some fixed temperature. The SAE Motor Oil Viscosity Grade Classification System (see chart above) uses these viscosity seconds to specify the viscosities of its SAE 5W, 10W, 20W, 20, 30, 40 and 50 motor oil grades. The first three "W" grades are especially suited for winter use.

The viscosity of your motor oil is very important. When you start your engine at a subzero temperature, a heavy, slow-flowing oil takes much too long to reach engine parts and permits more wear than thousands of miles of driving. However, a light, fast-flowing winter oil does not have enough viscosity to prevent wear at high summer temperatures. Thus, with ordinary oils, it is necessary to change grades seasonally.

Havoline Special 10W-30 Motor Oil is the wisest choice for any car owner because it magically combines the fast-flowing property of the Winter SAE 10W grade with the high temperature, wear-preventing quality of the Summer SAE 30 grade. It's the ideal, all-temperature oil. Use it *in all seasons.*

In addition, Texaco's special refining and exclusive additives in Havoline Special 10W-30 prevent the harmful sludge deposits and varnish that are so prevalent with ordinary oils in today's stop-and-go driving.

The few extra pennies for this finest of motor oils is your best insurance against engine damage and repair bills. See your Texaco Dealer for a change to Havoline Special 10W-30 ...and change it *regularly.*

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For more information about Texaco Car Oil 1960 HDW, call the nearest Railway Sales Division Office. There's one in Atlanta, Chicago, New York, San Francisco, St. Louis and St. Paul. Or, write Texaco Inc., *Railway Sales Division,* 135 East 42nd Street, New York 17, N. Y.

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